Methods to Optimize for Energy Efficiency

Developed by

David J. Moorhouse

& David M. Pratt

Air Vehicles Directorate

U.S. Air Force Research Laboratory

Presented by:

José Camberos & John Doty

Thermodynamics: Can Macro Learn from Nano?

22- 15 May 2011, Sweden

Cleared for Public Release: 88ABW-2008-1174

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
MAY 2011	**N/A**	**-**

4. TITLE AND SUBTITLE	
Methods to Optimize for Energy Efficiency	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Vehicles Directorate U.S. Air Force Research Laboratory**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA553749. Thermodynamics: Can Macro Learn from Nano? Held in Sjobo, Sweden on May 23-25, 2011. Approved for public release; distribution is unlimited. U.S. Government or Federal Purpose Rights License., The original document contains color images.

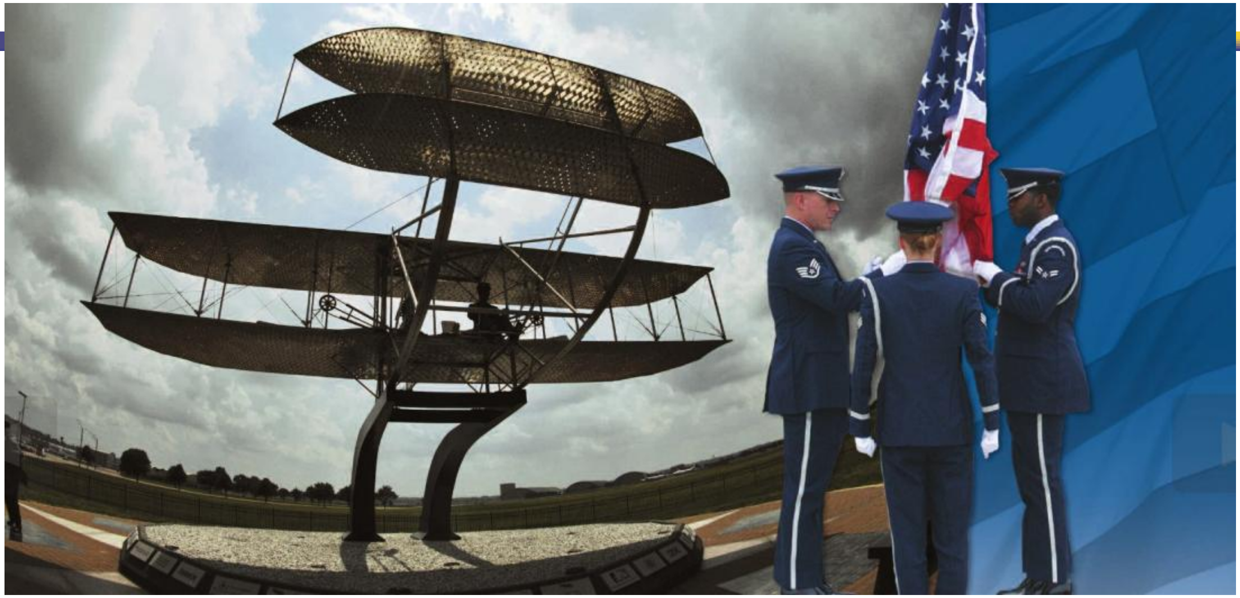
14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**33**	

Wright-Patterson AFB…

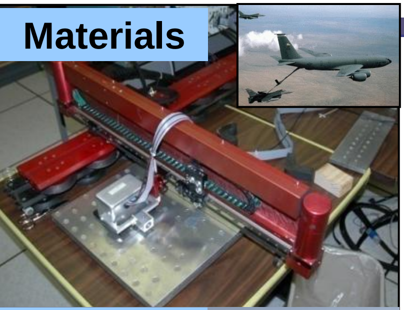
is the birthplace, home and future of aerospace



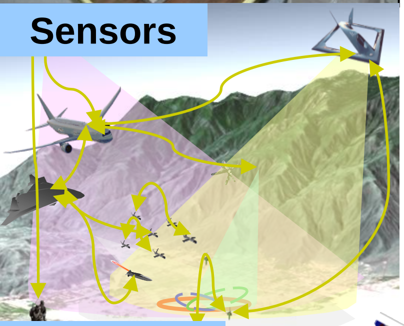
- On base organizations; missions ranging from acquisition & logistics management to research & development, education, flight operations and many other defense related activities
- Wright–Patterson Air Force Base (WPAFB) is the home of
  - U. S. Air Force Research Laboratory
  - Organizations that support for over 100 Air Force entities
  - U. S. Air Force Institute of Technology
  - National Museum of the U. S. Air Force
  - …

U. S. Air Force Research Laboratory

Materials



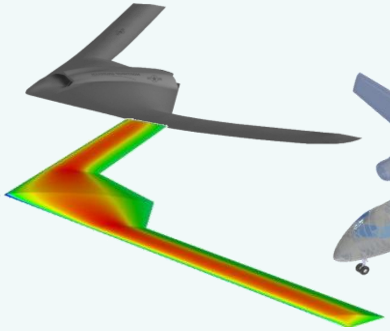
Sensors



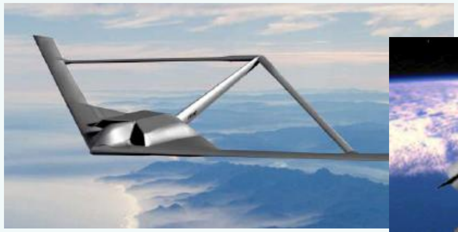
Weapons

Directed Energy

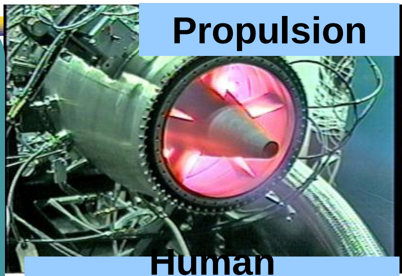
AERONAUTICAL SCIENCES	STRUCTURES	CONTROL SCIENCES



Air Vehicles Directorate

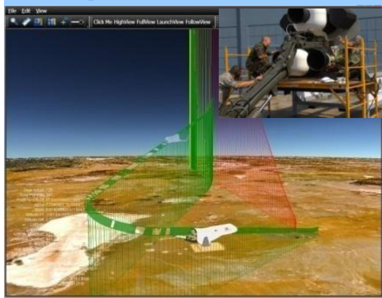


Propulsion



Human Effectiveness

Space Vehicles

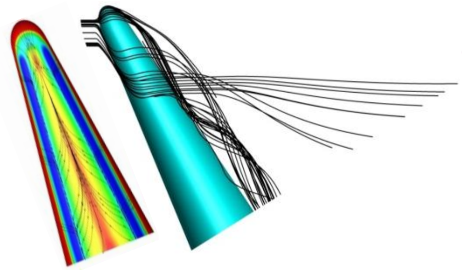


Information

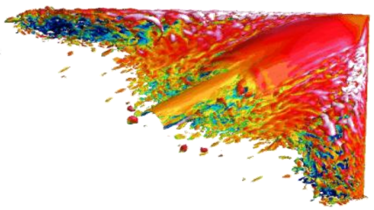
AFOSR – Basic Research

Air Vehicles Directorate
Core Technical Competencies

Aeronautical Sciences



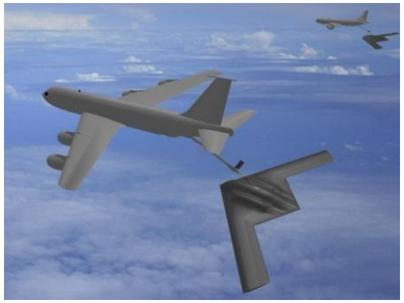
Hypersonics



- ★High Fidelity Computational Simulation
- ★Advanced Air Vehicle Concepts

Control Sciences

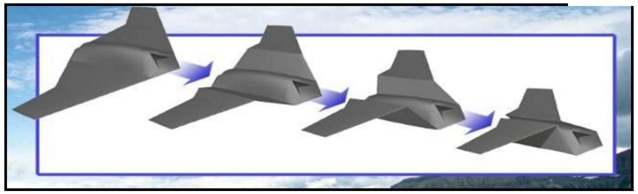
Collision avoidance



UAS range & endurance via aerial refueling

- ★Cooperative and Adaptive Control
- ★Autonomous and Advanced Control

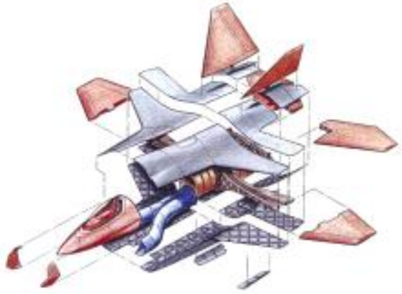
Structures



- ★Advanced Structural Concepts
- ★Multidisciplinary Structural Design & Analysis

Integration

Lightweight, Survivable Inlets



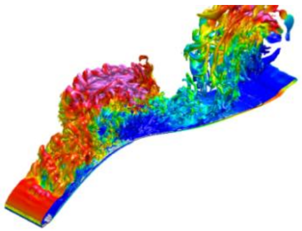
- ★Modeling and Simulation
- ★Quantitative Technology Assessment
- ★Experimental Validation

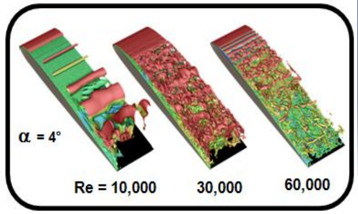
Air Vehicles Directorate
Research Centers

Computational Sciences

Dr. Jack Benek (ST)
Director, CS Center

Micro Air Vehicles

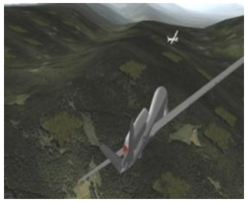




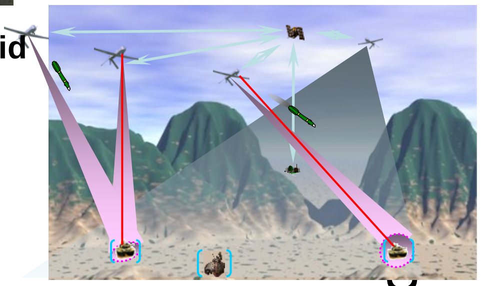
Low-Re Flow

- High Fidelity Computational Simulation

Control Sciences



Sense And Avoid

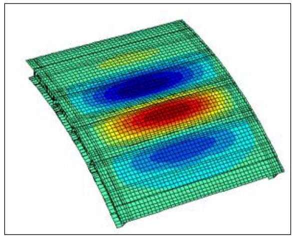


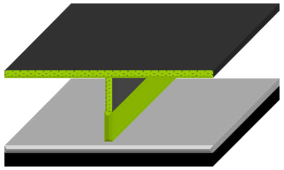
Dr. Siva Banda (ST)
Director, CS Center

- Cooperative and Adaptive Control

Structural Sciences

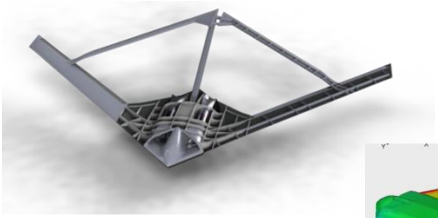
Dr. Ravi Chona (ST)
Director, SS Center

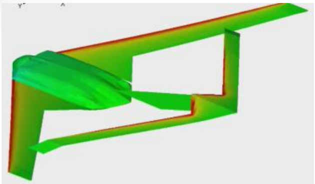




- Combined Extreme Environments

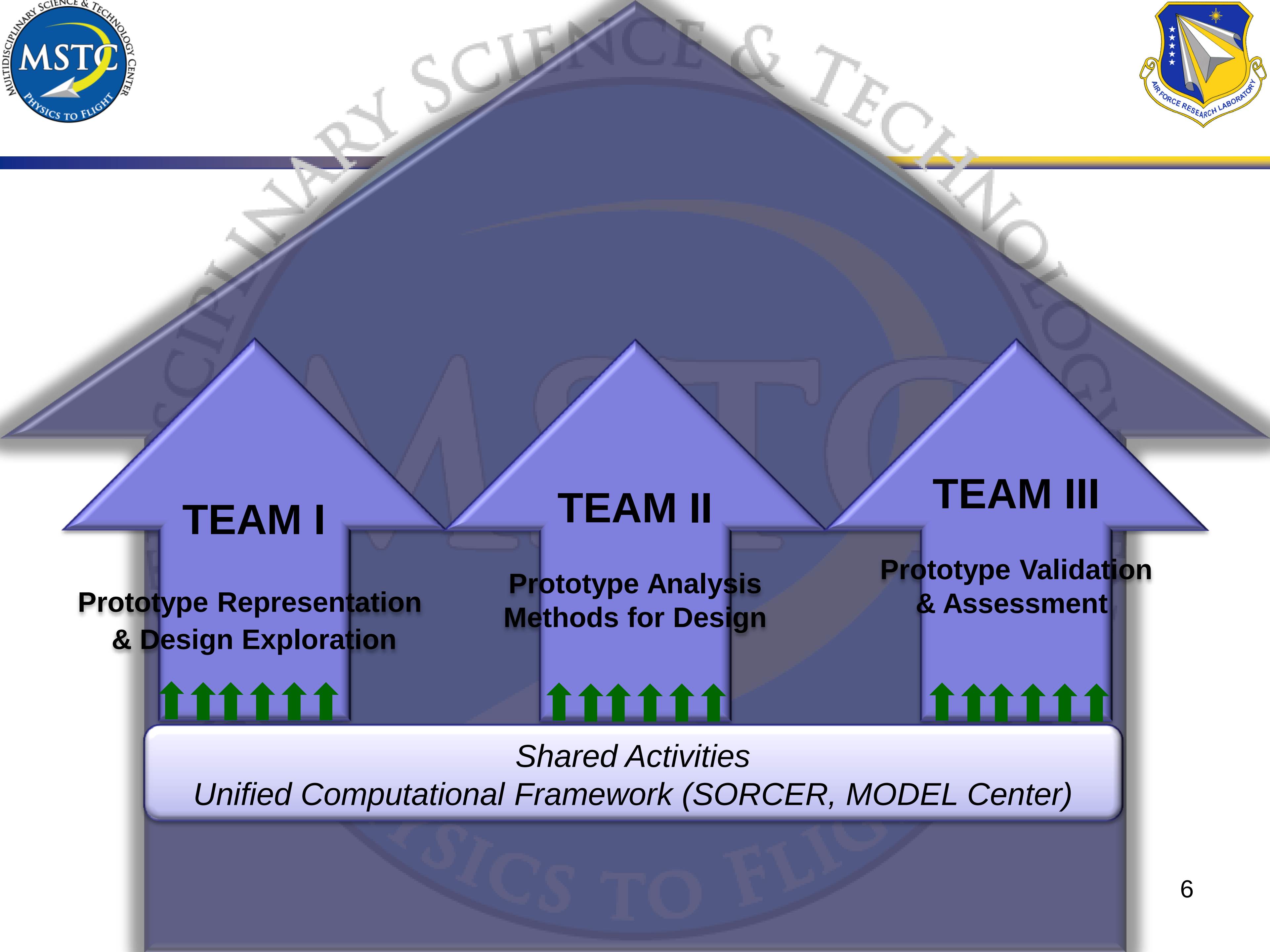
Multidisciplinary Science & Technology





Dr. Ray Kolonay,
Acting Director
MSTC Center

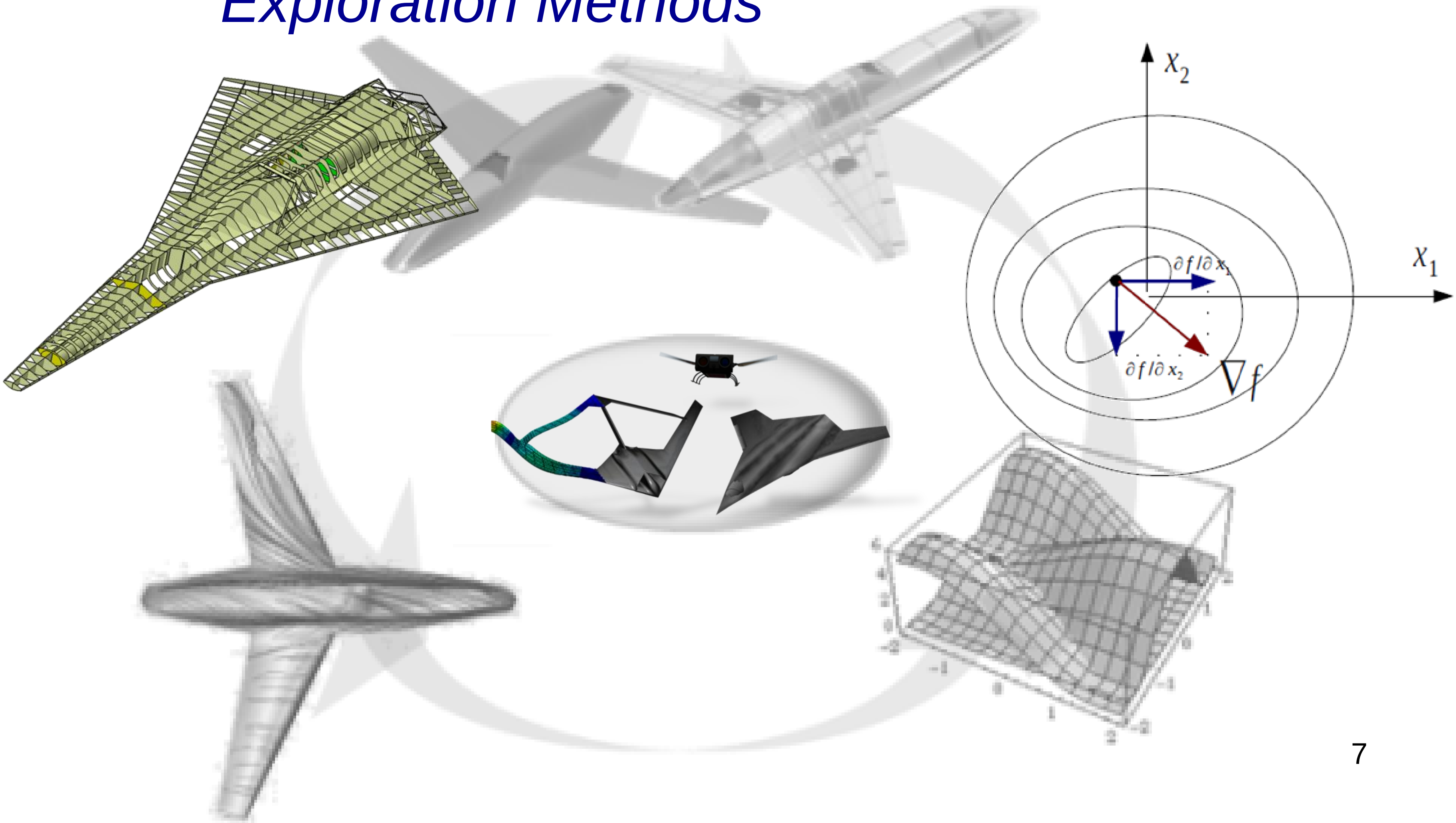
- Multidisciplinary Analysis & Design
Space Exploration



TEAM I
Prototype Representation & Design Exploration
TEAM II
Prototype Analysis Methods for Design
TEAM III
Prototype Validation & Assessment
Shared Activities
Unified Computational Framework (SORCER, MODEL Center)

Team 1: Prototype Exploration

– *Prototype Representation & Design Exploration Methods*



Feature Presentation

EXERGY-BASED METHODS

Energy-Based Design Methods Background

Historically:

- Energy always an *implicit* consideration, e.g:
  - Breguet Range Equation ~ Energy to overcome Drag
  - Trajectory Optimization ➔ trade Potential & Kinetic Energy

Problem:

- Energy Considerations are Only Implicit & unrelated.
- Aircraft Subsystems are ‘Optimized’ as Separate Components.
- “Integration” accomplished, but often with incompatible objectives

Need Common Metrics for Analysis and a Design Framework to Apply at All Levels

Evolutionary vs. Revolutionary

"Polishing Old Methods Can Only Give Incremental Improvement, But New Methods Can Open the World"

ASSESS CUSTOMER REQUIREMENTS

EVOLUTIONARY SOLUTION	**OR**	REVOLUTIONARY
PRE-EXISTING DATA (Physical ~ even with approximations Validated with FLIGHT DATA!!)		THEORETICAL MODELS
VALIDATED TOOLS	⟺	WHAT TOOLS ??
EXISTING MDO PROCESS	⟺	ALLOW FLEXIBILITY
IMPROVE 'COMPONENTS' and/or INNOVATE	⟺	INVENTION, with PHYSICS

INCREMENTAL IMPROVEMENT CAN BE VERY GOOD OR ??

FIRST TIME CAPABILITY IS VERY GOOD

Customer and Overhead Work

- Define specific energy as kinetic + potential energies per unit mass:

$$E = h + \frac{1}{2g}U^2$$

- *Customer work rate* – includes generating specific payload energy & overcoming drag and power requirements:

$$\frac{dw_c}{dt} = W_p \frac{dE_W}{dt} + P_P + D_P U$$

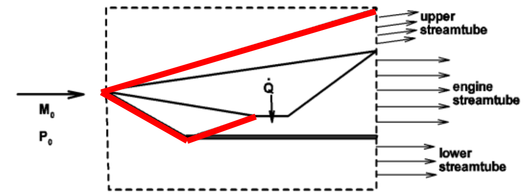
- *Overhead work* – Sum of work consumed and drag caused by every component of the system:

$$\frac{dw_o}{dt} = \sum \left(W_i \frac{dE}{dt} + P_i + D_i U \right)$$

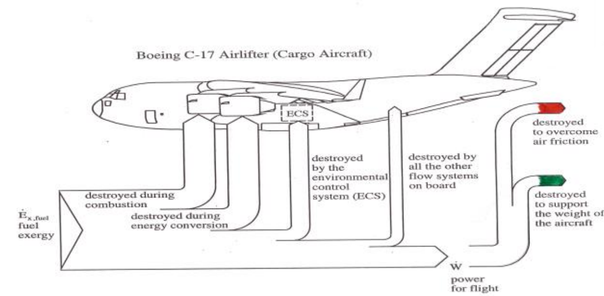
Design Problem ➔ Minimize Overhead Work (Loss)

AFRL Energy-Based Design

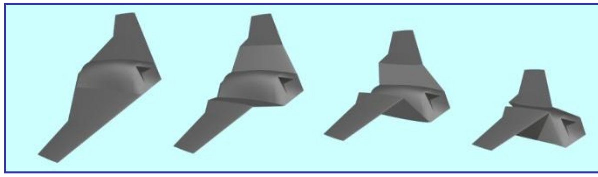
Develop Thermodynamics Laws into common currency for system optimization,
e.g. hypersonic airframe/propulsion integration



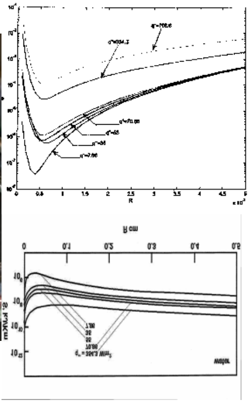
Develop energy-minimizing algorithms based on consumption, so every subsystem component is optimized to system-level metrics



Develop topology and mechanization to enable energy-efficient adaptive structures for fully morphing aircraft concepts



Develop methodologies for entropy generation minimization and optimization of thermal components



Additional tasks:
Understand and develop energy harvesting

High fidelity computation of entropy generation

Exergy-Based Design Methods:

Specify all vehicle design requirements as work potential (exergy destruction, entropy production)

Multidisciplinary Design:

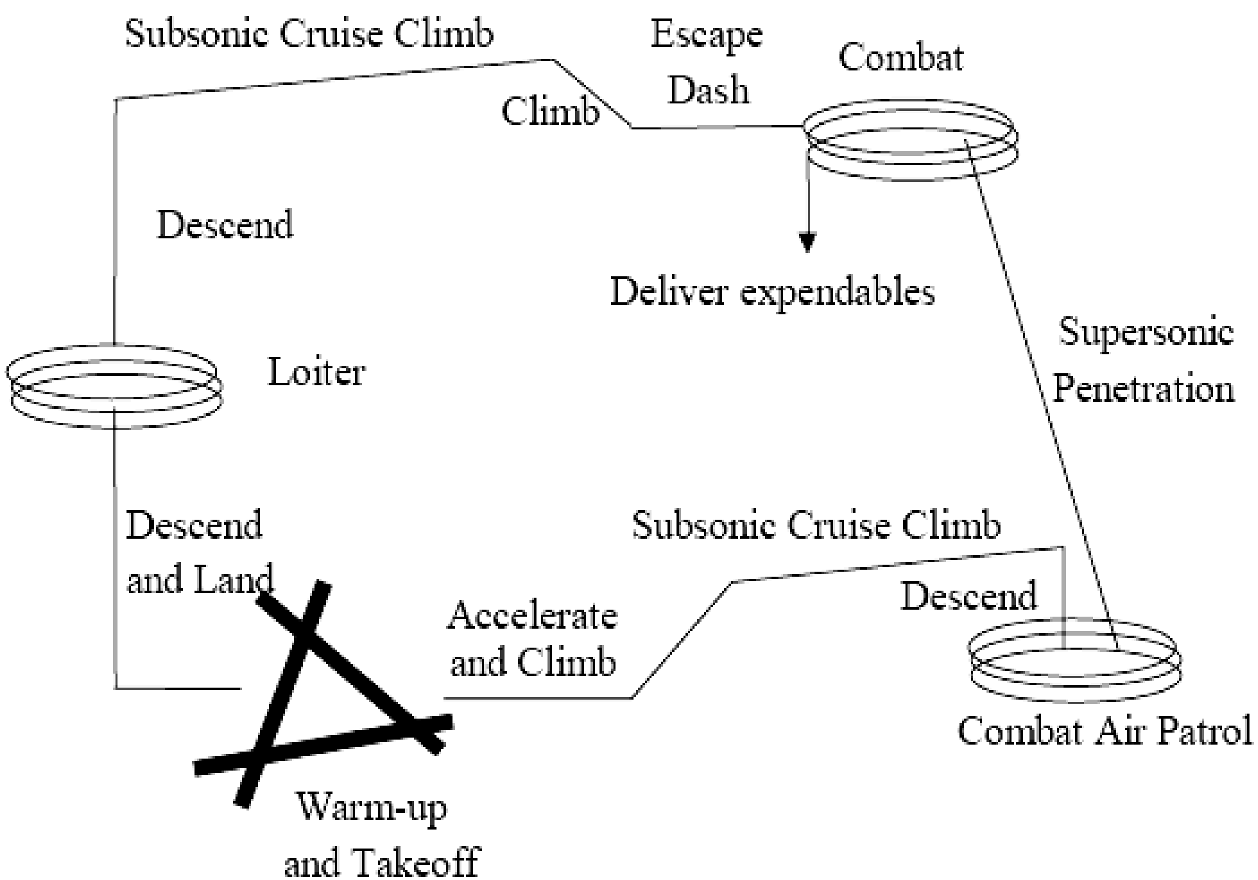
- Decompose system into energy subsystems
- Design all components to optimize system to minimize loss

Example

MISSION LEVEL OPTIMIZATION

Mission Level Optimization

Mission for an Advanced Aircraft Fighter (AAF):
PS, ECS, and AFS-A



Source: Mattingly et. al., 1987

Mission Segments	
No.	Name
1	**Warm-up**
2	**Take-off acceleration**
3	**Take-off rotation**
4	**Accelerate**
5	**Climb**
6	**Subsonic cruise climb 1**
7	**Combat air patrol**
8	**Supersonic penetration**
9	**Combat turn**
10	**Combat acceleration**
11	**Escape dash**
12	**Subsonic cruise climb 2**
13	**Loiter**
14	**Descend and Landing**

Optimal Vehicles Predicted for Four Optimization Metrics

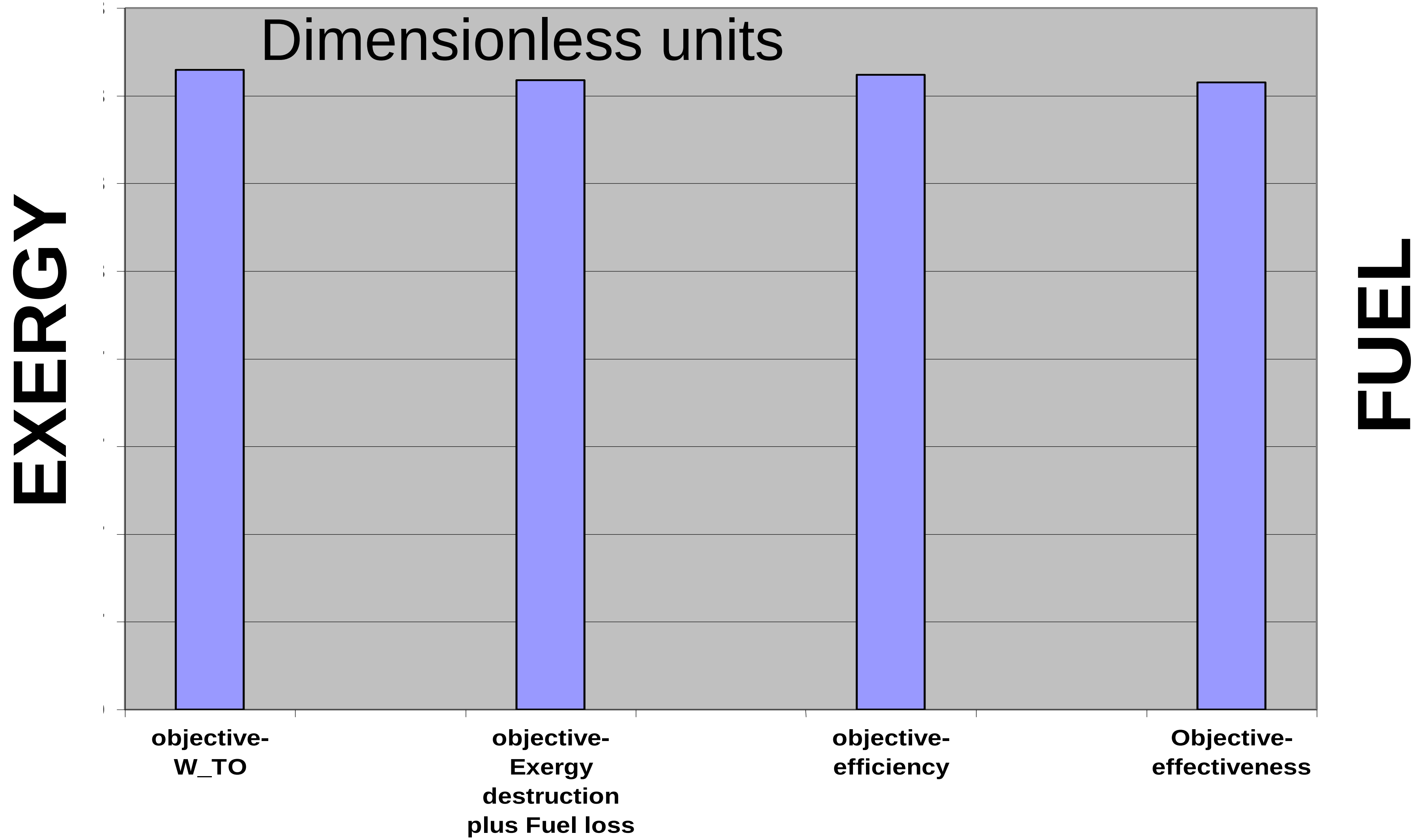
Traditional:

- Minimize Gross Takeoff Weight

Exergy Methods:

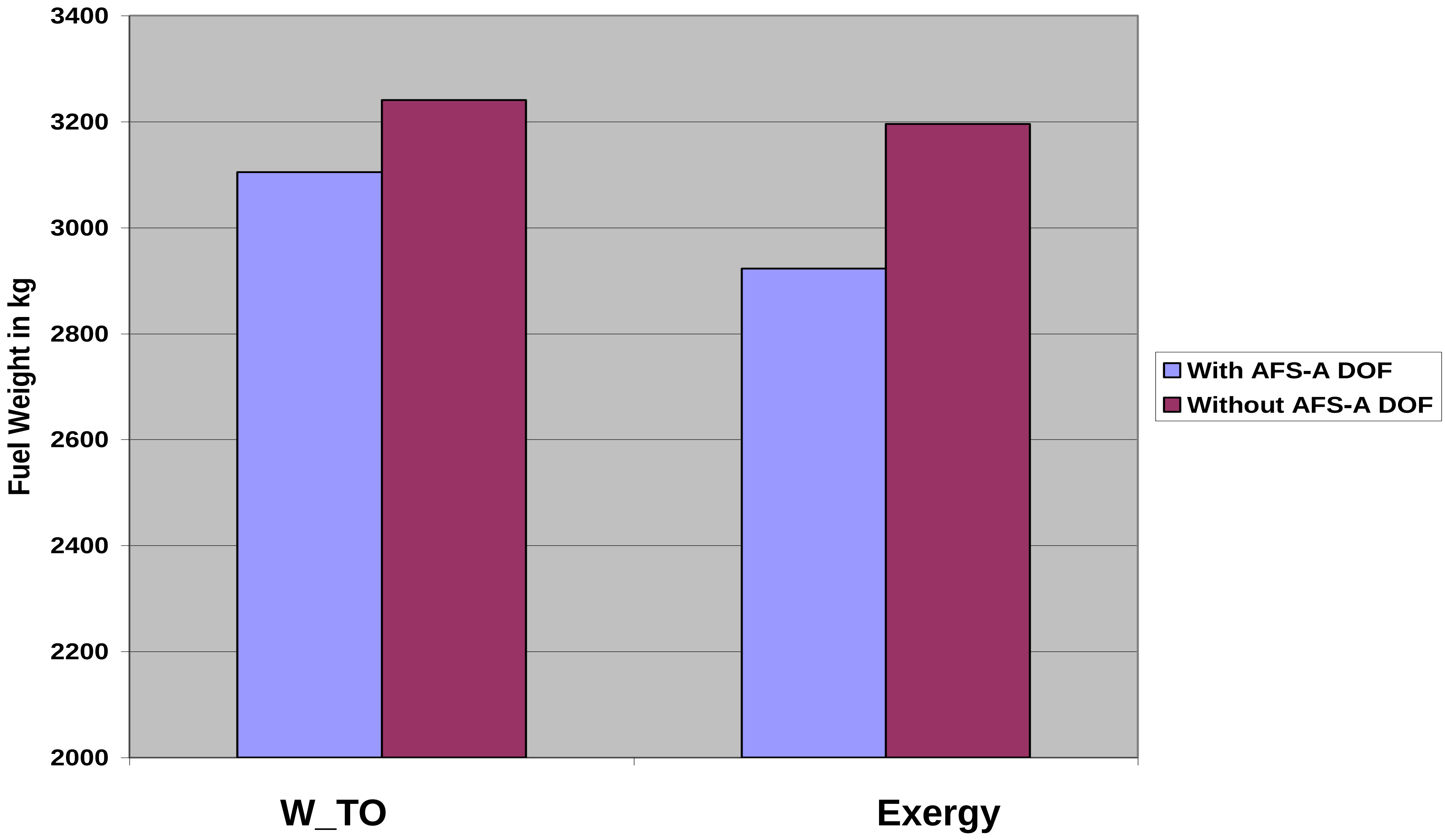
- Maximize Thrust Efficiency = thrust divided by fuel mass flow x heating value
- Maximize Thermo Effectiveness = thrust divided by max thrust if no irreversibilities
- Minimize Exergy Destruction

Optimal Vehicles Predicted for Four Optimization Metrics



Optimization Metric Makes Little Difference ~~~ SO ????

Optimum Vehicles Including Aero Design Variables



Example

MORPHING WING MISSION ANALYSIS

Morphing Wing Mission Analysis

Wing Optimization Details:

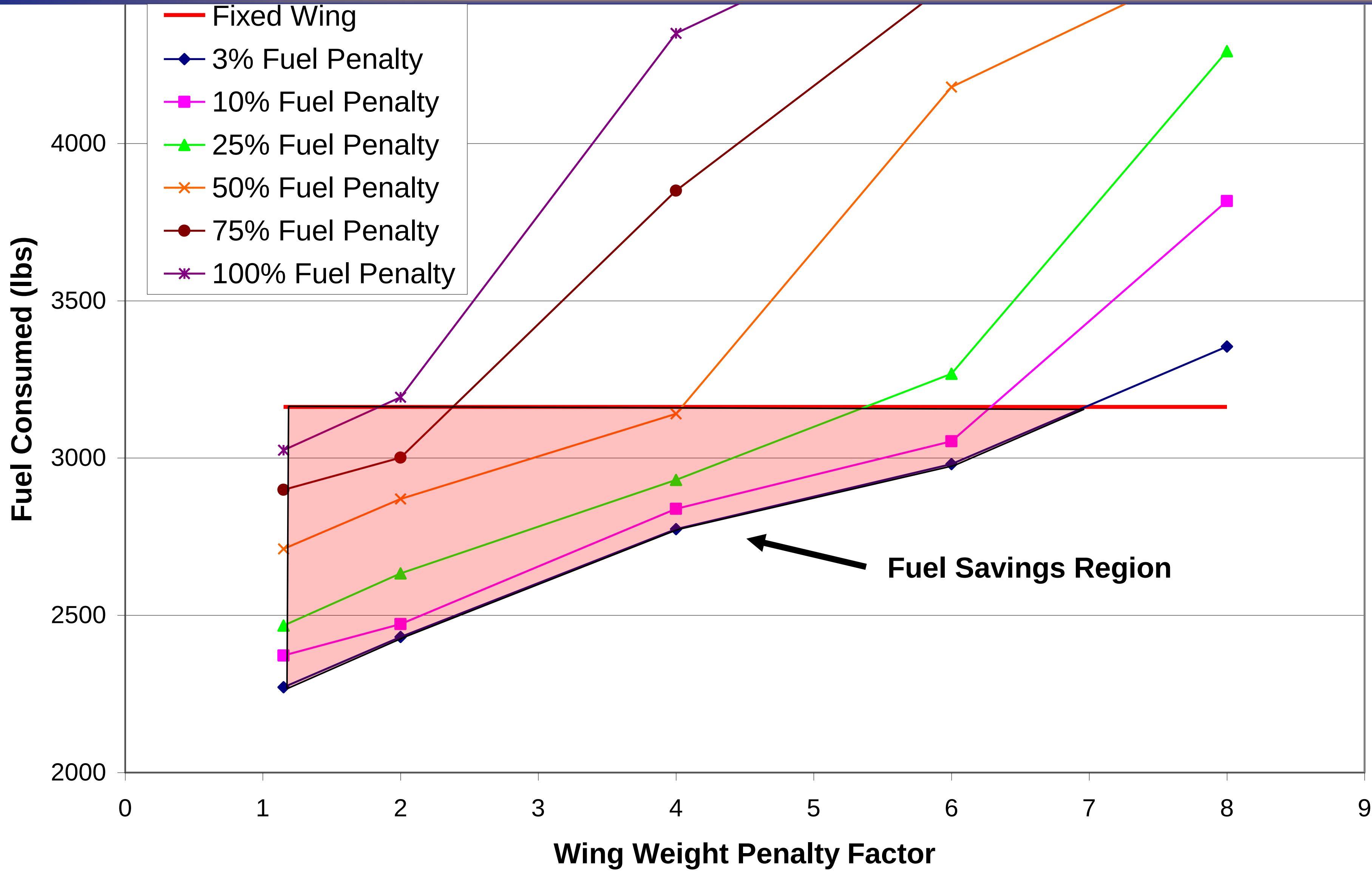
- Wing sweep, wing length, root and tip chord lengths (2D geometries) are morphed, mission optimized by segment
- Wing twist and camber changes (3-D geometries) are <u>not</u> morphed

- 15% weight penalty factor > varied up to 9 x baseline weight
- 3% fuel penalty factor > varied up to double baseline mission fuel

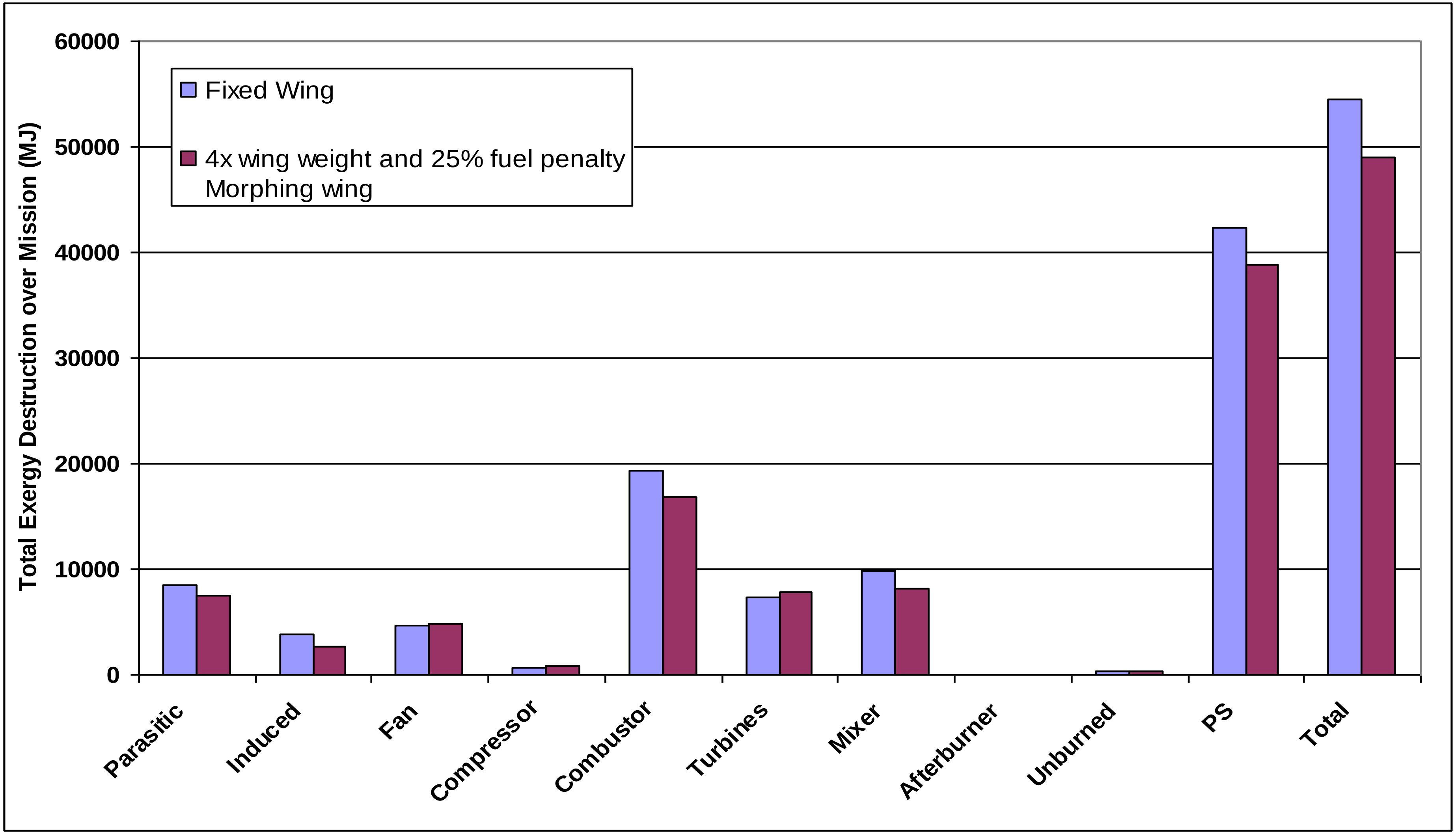
Model Characteristics

- Turbojet propulsion subsystem (PS)
- Airframe subsystem
- Genetic algorithm (QMOO)
- Investigated mission effects of using morphing wing technology on supersonic fighter aircraft

Effect of Morphing Wing on Exergy Destruction



Exergy Destruction Distributions



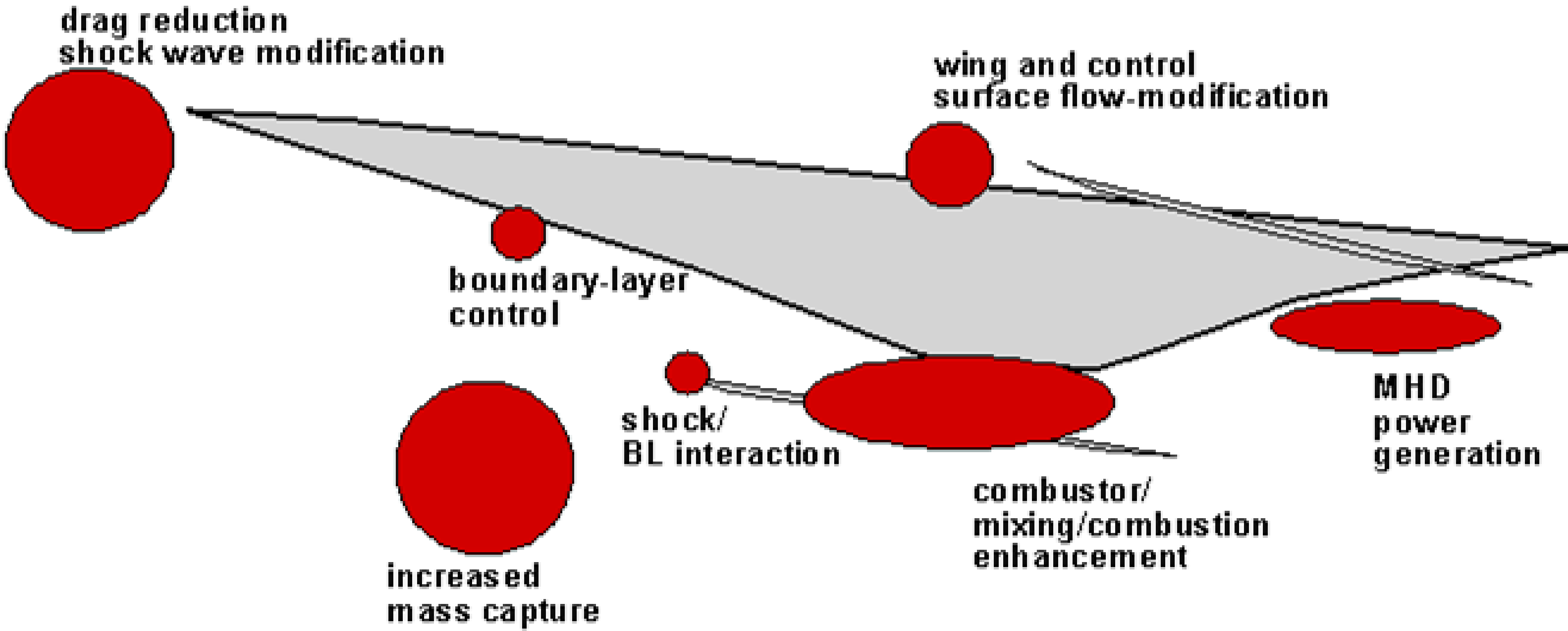
Effect on Different Mission Segments

	Morphing Wing		Fixed Wing	
Mission Segment	Cruise	Supersonic Penetration	Cruise	Supersonic Penetration
Wing length (ft)	35.50	29.09	41.4301	
Wing sweep (deg)	13.16	43.63	41.7168	
Root Chord Length (ft)	4.04	4.00	5.0138	
Tip Chord Length (ft)	1.53	1.68	2.6809	
Fuel Consumption (lbm)	76.8	712.2	210.1	662.2
Percent Decrease	63.4%	-7.55%	Baseline	

Example

ENERGY DEPOSITION

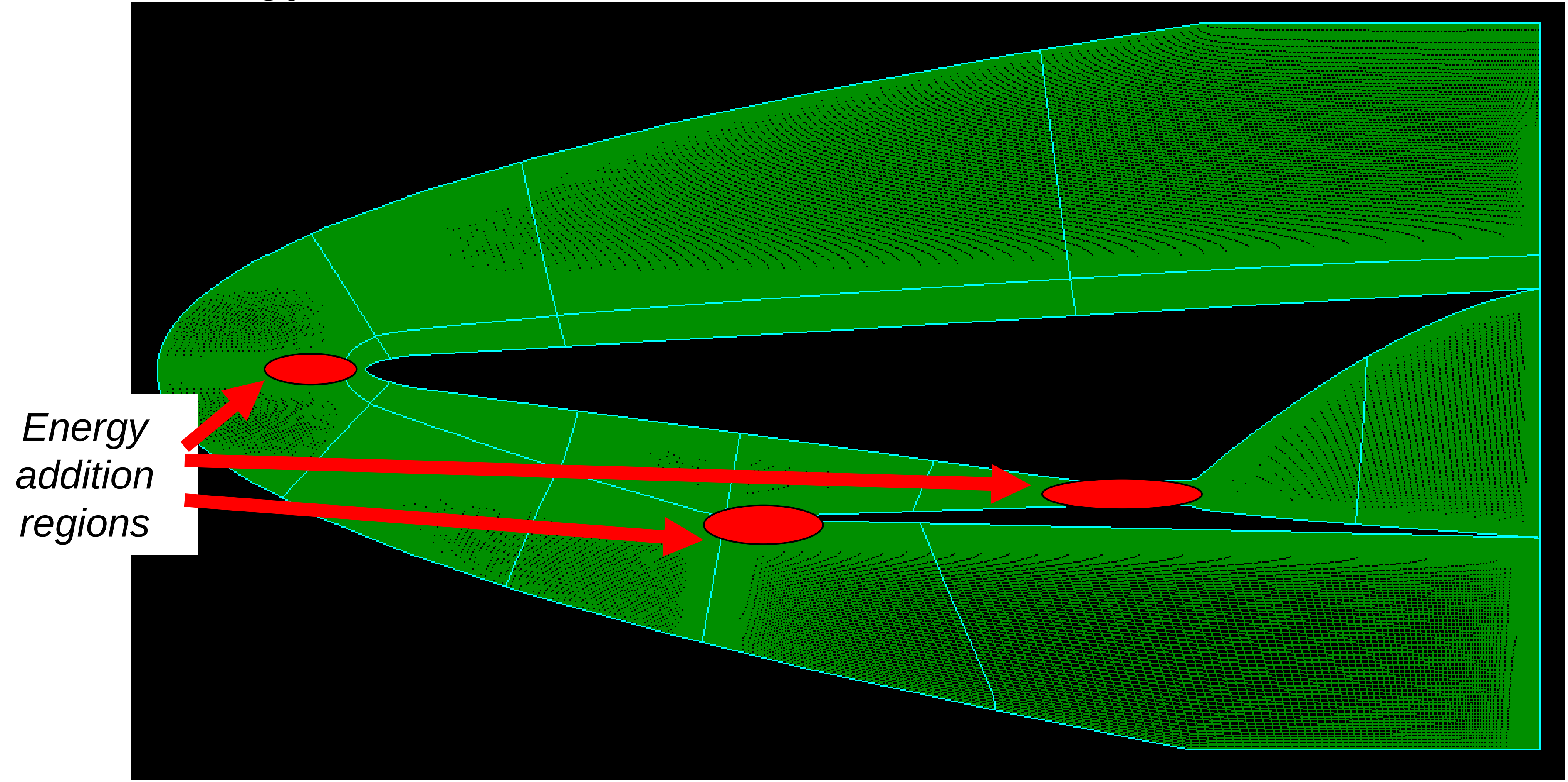
Potential Areas of System Usage for On-board Energy



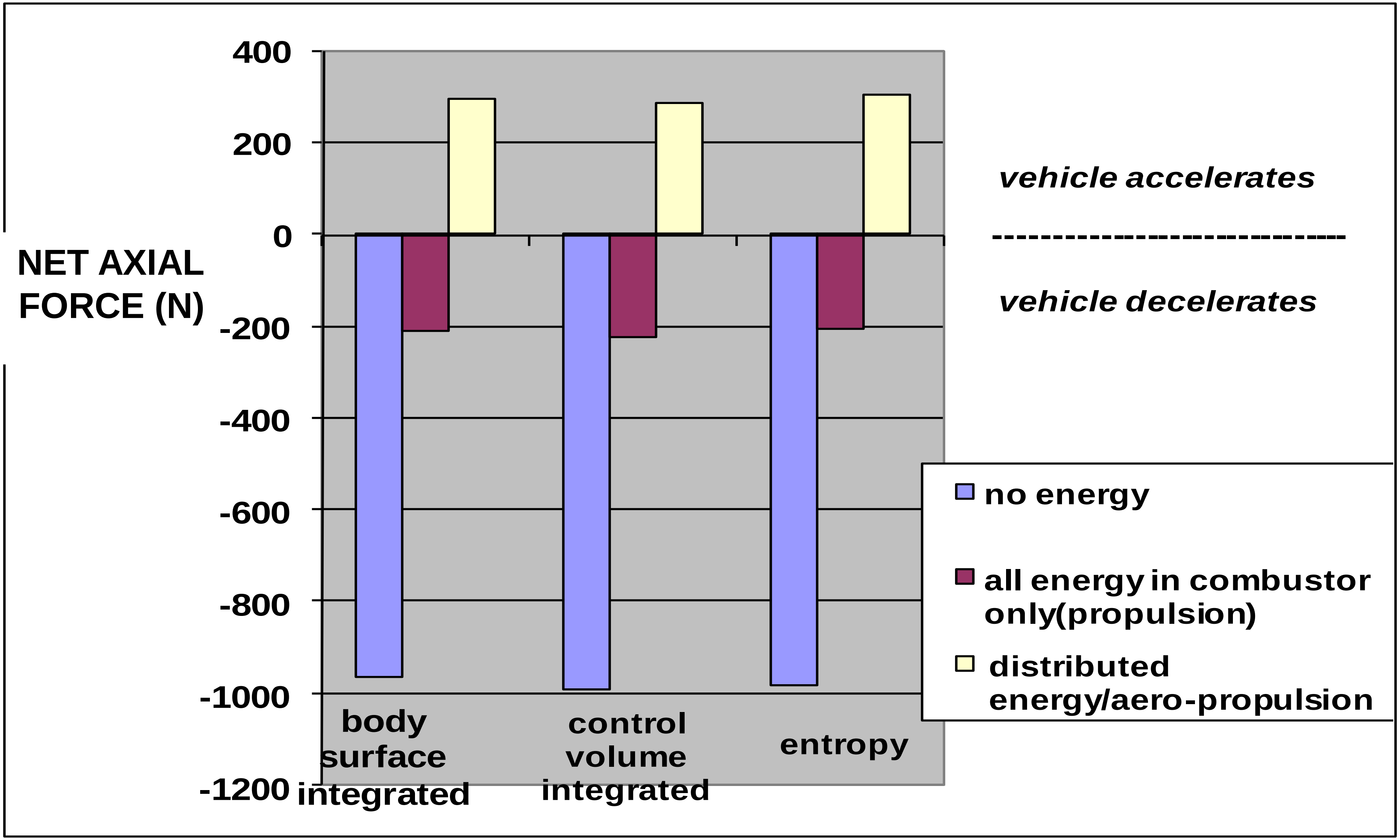
Requires Accurate & Consistent Second-Law-Based, System-Level Performance and Optimized Fuel Usage

2-D Vehicle Study

- Used VULCAN "ignition sub-blocks" to add energy into discrete locations in the flow-field



2-D Vehicle Force Summary Mach 10

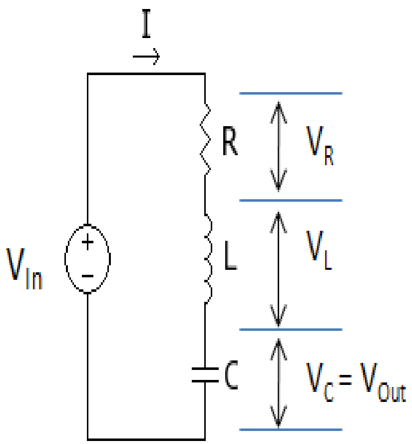


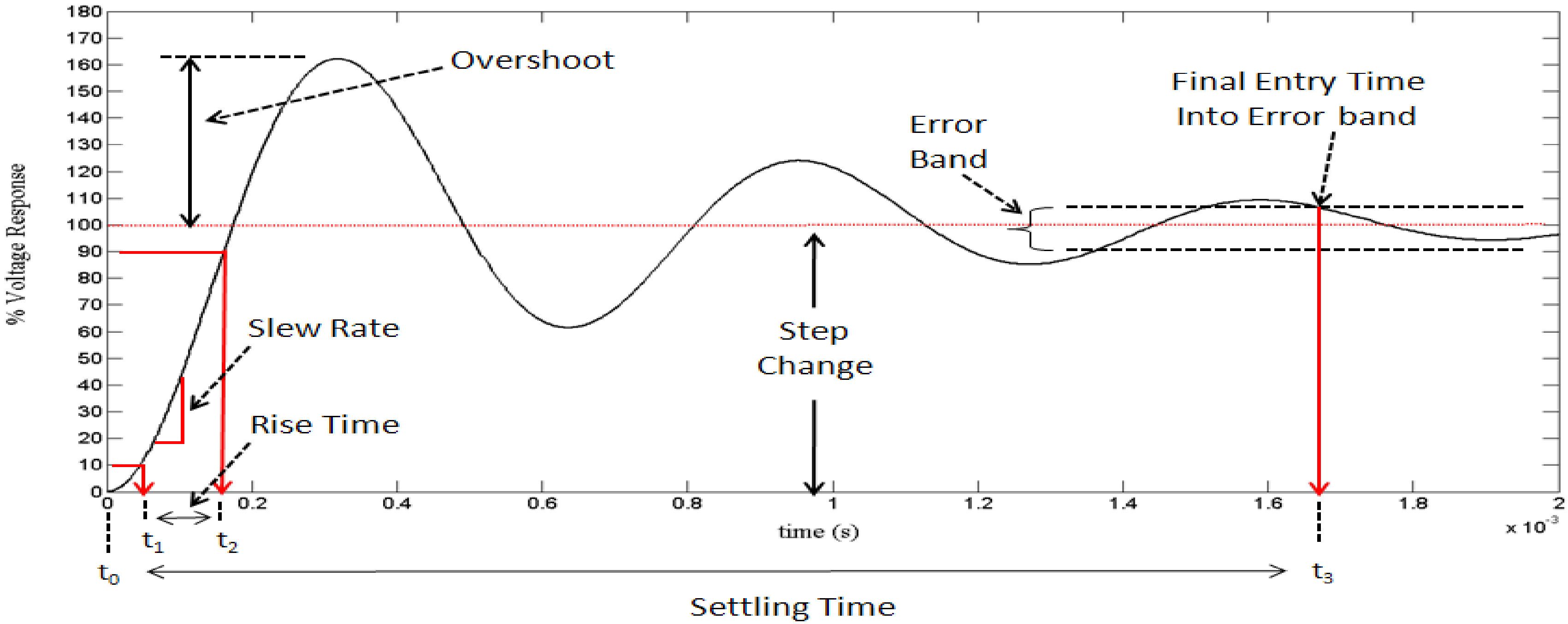
Example

ENTROPY GENERATION MINIMIZATION & MAXIMUM SYSTEM PERFORMANCE

System Dynamics

- Step input change in source voltage (V_C):
  - *Rise time:* Time for (V_C) 10% to 90% of *step change*
  - *Slew rate:* Maximum (V_C) change rate
  - *Overshoot:* Maximum normalized (V_C)
  - *Settling time:* Elapsed time for meta-stability



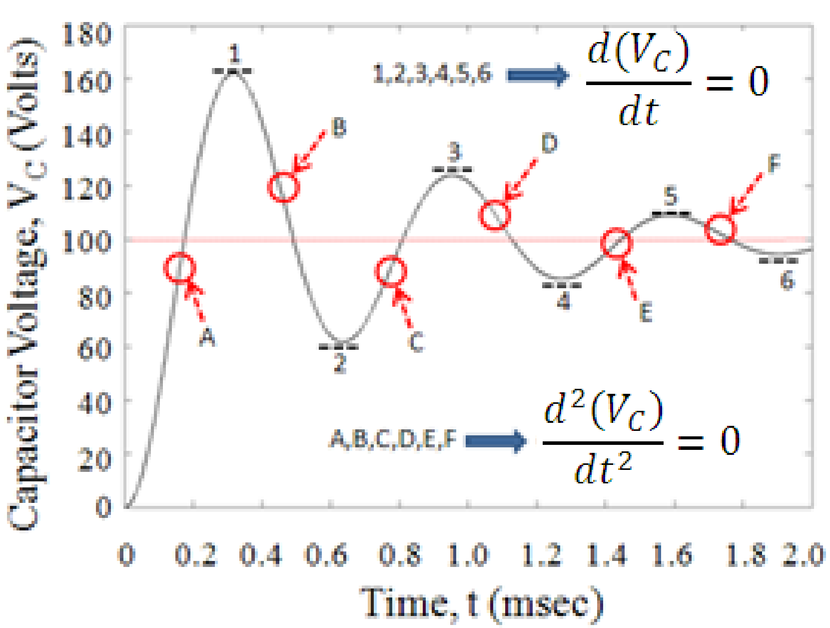


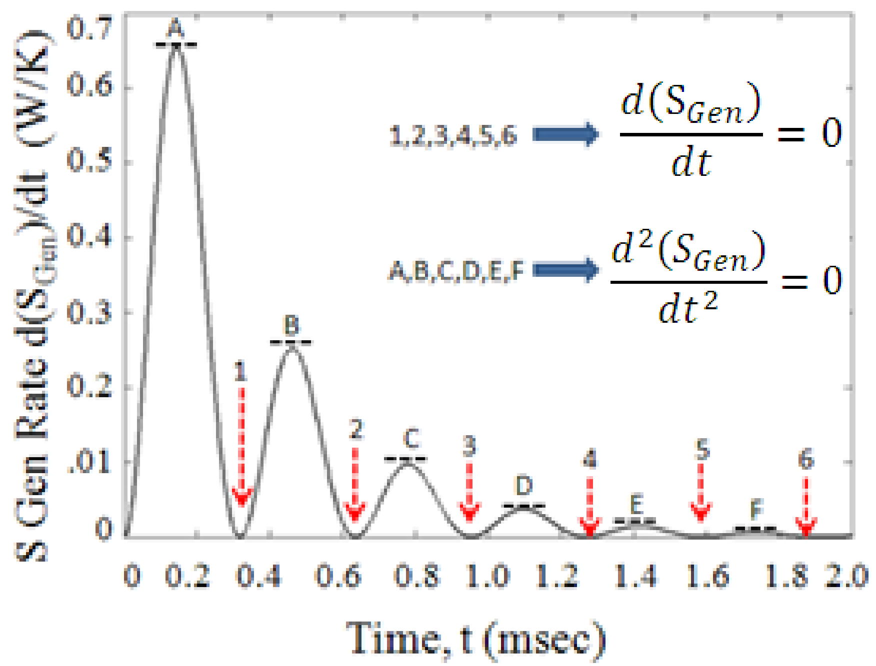
Dynamic Response

1st & 2nd Law Comparison

★ 1st Law (V_C)→ $\frac{d(V_C)}{dt} = 0$

★ 2nd Law (Entropy)→ $\frac{d^2(S_{Gen})}{dt^2} = 0$



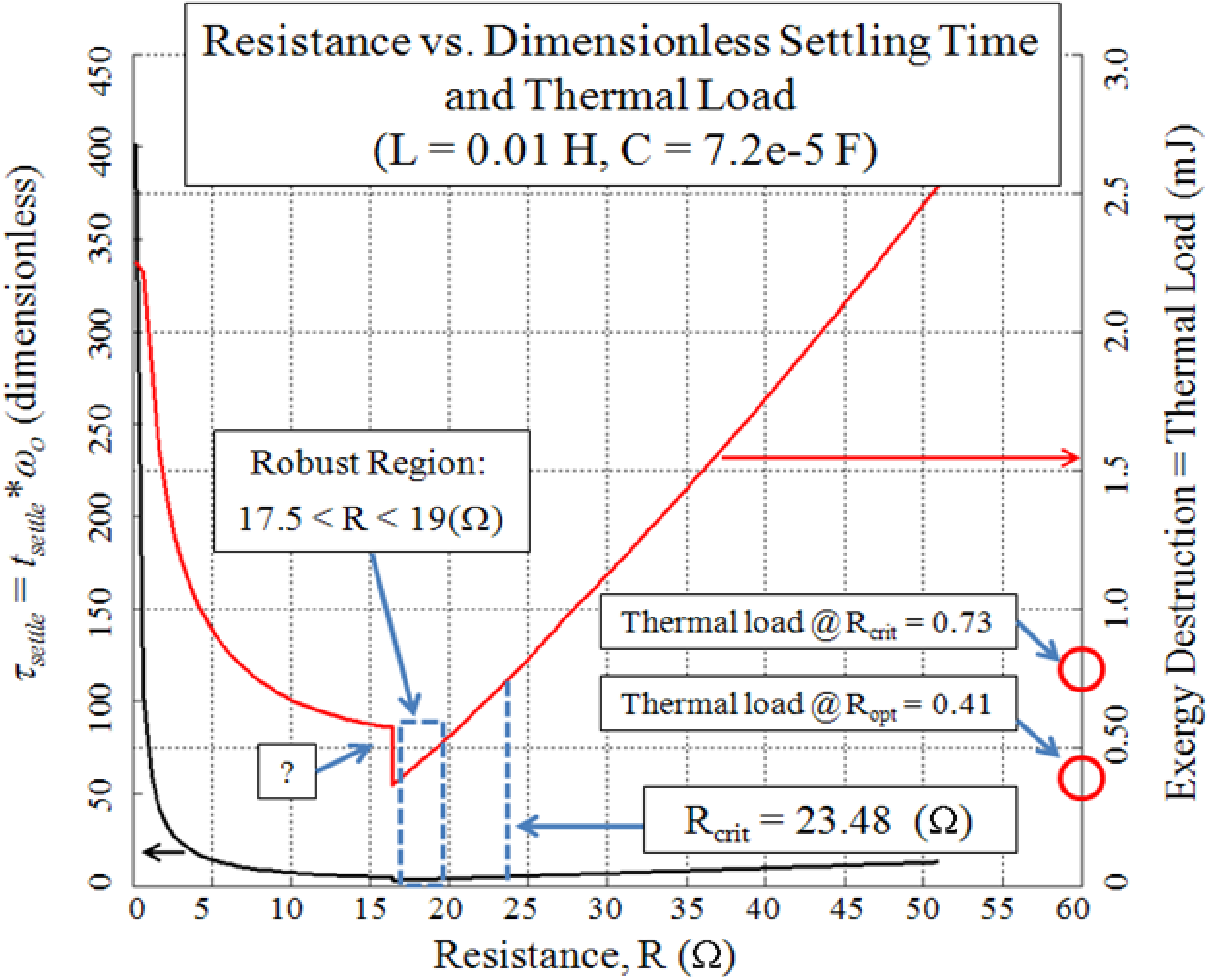


SAME PHYSICS; BUT DIFFERENT INTERPRETATION:

1st & 2nd LAW → STATIONARY POINTS, → EQUILIBRIUM OR NOT?

Interpretation

Dynamics AND *Exergy Destruction*



~29% lower Rise Time & Settling Time, with ~43% reduction in Thermal Load; 2% Overshoot

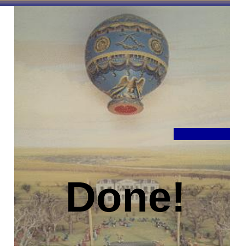
"Anomaly" in exergy destruction due to settling time definition

DYNAMIC BEHAVIOR CAPTURED VIA STATIONARY INPUTS

MIN THERMAL LOAD & MIN EXERGY DESTRUCTION→~INCREASED PERFORMANCE

Exergy-Based Design Methods

Summary:



- Optimization metric options are equivalent for propulsion + power components
- Adding airframe component ➔ optimizing to minimize exergy destruction saved 6% fuel
- Morphing wing ➔ significant system benefits
- Net thrust demonstrated with strategic energy deposition, using work potential loss

Exergy-Based Design Methods MUST be used to enable truly integrated, system/mission-level analysis and design optimization

Research Questions

- What are relevant time scales for dynamic systems?
- How to incorporate dramatically different timescales into cohesive system?
- How to appropriately define system and its relevant boundaries such that interactions properly captured?
- How to properly pose the physical problem such that the models are more correctly developed
- How to validate models with physical experiments?